Jaromír Demek
Brno

CRYOGENE PROCESSES AND THE DEVELOPMENT OF CRYOPLANATION TERRACES

Abstract

In this paper the author deals with the evaluation of the significance of various cryogene processes in the development of cryoplanation terraces. He states that their intensity and significance change in dependence on the stages of the terrace development.

INTRODUCTION

The cryoplanation terraces are an important part of the relief of numerous highland and mountainous areas in which cryogene processes are acting or were acting in the past.

The problem of the origin of cryogene terraces was solved in principle in the works of S. V. Obruchev (1937), S. G. Boch and I. I. Krasnov (1943, 1946, 1951). These authors have proved that cryoplanation terraces are denudation forms developing due to the activity of a complex of cryogene processes. A number of important problems remain unsolved, in spite of the fact that the question of the origin of those forms has been already solved in principle. One of them is even the evaluation of the significance of the individual cryogene processes in the development of cryoplanation terraces. The discussion of the problem mentioned is the subject of this paper.

The studies on cryoplanation terraces carried out till now have shown that a number of cryogene processes take part in their development. These processes can be divided into two groups, such as:

(a) the processes disintegrating the bedrock and preparing the loose material;

(b) the processes transporting the prepared loose material.

Frost weathering, nivation and frost sorting belong to the first group. Solifluction, surface and subsurface transportation by running water, supranival processes and deflation can be ranged into the second group.

The views of the authors of the significance of the individual cryogene processes in the development of cryoplanation terraces differ considerably. The opinions concerning the significance of solifluction and removal by running water are especially different.

The analysis of the literature on cryoplanation terraces (*cf.* G. F. Gravis, 1964) and the author's proper research in Europe, Siberia and the U.S.A. show that the intensity and significance of the individual processes change in dependance on the stages of the terrace development.

PROCESSES ACTING IN THE FIRST STAGE OF THE DEVELOPMENT OF CRYOPLANATION TERRACES

Observations of most authors show that in the first stage of the development of cryoplanation terraces nivation processes taking place in the surroundings of permanent or temporary snow patches are of main importance. Snow accumulating in an irregularity of the terrain supplies water during its melt even in the period when the surrounding terrain is less moistened and the cryogene processes dependent on water are already slower. In the surroundings of the snow patch the cycles of thawing and re-freezing are more frequent than in drier places (L. H. McCabe, 1939, p. 454). Due to this fact fundamental preconditions for the development of a denudation form are created.

In case that the snow patch rests on bedrock the thawing water penetrates into the fissures and more intense frost weathering takes place in the neighbourhood of the snow patch than in the more distant surroundings. If the snow patch rests on debris more intense frost sorting of the material occurs in its neighbourhood. The material prepared is then removed by means of running water and solifluction. L. H. McCabe's observations have shown (1939, p. 455—456) that linear removal by the water running in tunnels can take place even below the snow patch. The material of the upper slope sections is then transported on the snow patch surface by means of supranival processes (*cf.* e.g. A. Jahn, 1961).

Due to the activity of the processes described the original irregularities increase and a nivation hollow or a nivation bench develops. In this connection several problems arise, such as:

(a) The possibility of snow accumulation requires the presence of undulations on slopes. Two eventualities are to be supposed here, namely:

(aa) the presence of the undulations already prior to the starting of the cryogene processes,

(ab) the creation of the irregularities directly through the cryogene processes as for instance through the jointing of the surface in polygonal fissures or frost scars in which snow accumulates (*cf.* A. I. Popov, 1960, p. 29—30) or through the development of solifluction terraces at the foot of which snow can also accumulate (*cf.* A. M. Kropachev & T. S. Kropacheva, 1956).

The unequal occurrence, number and extent of the cryoplanation terraces on slopes even under identical geological conditions can be considered one of the proofs of the significance of the nivation processes in the terrace development.

(b) Most cryoplanation terraces have a sickle-shaped form and are elongated in one direction. On the contrary, in textbooks of geomorphology and geology the development of nivation hollows in cirques is supposed (*cf.* e.g. L.D. Leef & S. Judson, 1965, p. 183; H. H. Read & J. Watson, 1964, p. 223; A. Holmes, 1965, p. 648, and others).

Observations have shown that in one area e.g. on the main ridge of the Hrubý Jeseník Mts. in Czechoslovakia, in the mountain group Evota in the Aldanskoye Nagorye (mountains) in Siberia the development of cryoplanation terraces of cirque-like depressions can be observed. W. V. Lewis (1939, p. 153) and McCabe (1939, p. 450) have distinguished, according to the forms, two types of snow patches, such as circular snow patches and elongated snow patches. It may be stated that the elongated patches are more favourable for the development of cryoplanation terraces. But on the other hand the observations of the steep sections bordering the cryoplanation terraces show that they consist rather often of a number of convexly uparched sections. This can be explained either by the fact that the cryoplanation terraces develop due to the coalescence of several neighbouring hollows or that the elongated snow patch divides in midsummer into several smaller snow patches of circular shape. The second eventuality is more probable.

It may be accordingly summed op that in the first stage of the development of cryoplanation terraces the nivation processes are of greatest significance. The temporary snow patches melting in the second half of summer are acting most intensely. They are effective for the longest period of time and in the largest area.

PROCESSES ACTING IN THE SECOND STAGE OF THE DEVELOPMENT OF A CRYOPLANATION TERRACE

In the second stage of development the terrace consists already of a steep section (the so-called frost-riven cliff or frost-riven scarp) and of a terrace flat of an angle of slope of about 7°. Observations show that cryogene processes taking place on the individual parts of the terrace display partial differences.

On the frost-riven cliff or frost-riven scarp mainly nivation processes are acting. As long as the height of the tread corresponds to the thickness of the snow drift the intensity of moistening and accordingly also that of frost weathering on the whole cliff or scarp are the same. In the case of higher frost-riven cliffs or scarps the snow rests only at their foot. The upper part of the cliff especially its edge dries up sooner and the intensity of frost weathering is smaller. On the contrary the intensity of frost weathering is higher at the foot and the cliff or scarp is undermined. Especially in mountainous parts of Czechoslovakia the 20—30 m high overhanging frost--riven cliffs with a marked depression at their foots (e.g. Malínská skála Tor in the Českomoravská vrchovina Highlands, Pulčínské skály Tors in the Javorníky Mts., etc.) were studied. At the foot of frost--riven scarps bedrock outcrop can be found proving an intense weathering in the places moistened by the snow patch. The undermining of the foot induces then a parallel retreat of the frost-riven cliff or frost-riven scarp. The material falling down the upper part of the steep section is transported on the surface of the snow patch and accumulated often at its foot in form of a nivation ridge. The material is simultaneously carried away of the foot of the cliff or scarp that is in this way exposed to frost weathering (*cf.* Fig. 1).

In temperate subnival (periglacial) climate where soil humidity is greater and the upper edge of the frost-riven cliff or scarp dries up only for a shorter period, frost weathering takes place even in the upper part of the cliff. It is evidenced by the step-like arrangement of the cliff that can be clearly seen on the cryoplanation terrace in the Táborské skály Tors in the Hrubý Jeseník Mts. in Czechoslovakia (*cf.* Fig. 2).

The terrace flat is then a form on which the material comming

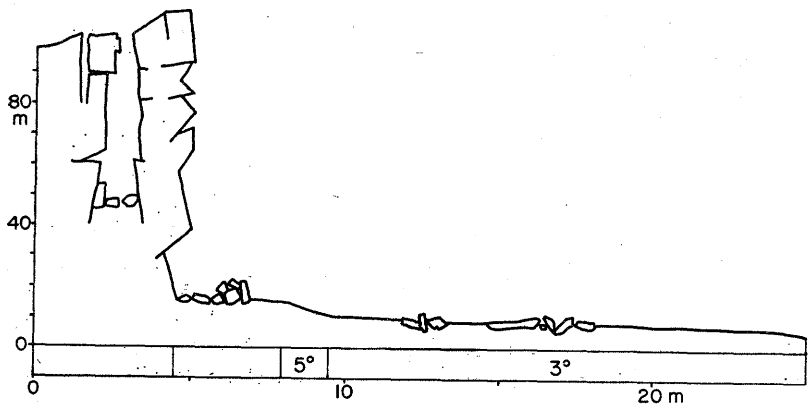

Fig. 1. Schematic sketch of the frost-riven cliff, in locality Na hradě in the piedmont of the Šumava Mts., with a protalus rampart at the foot
Levelled by J. Vařeka, constructed by J. Demek, 1965

from the frost-riven cliff or scarp is further sorted and transported. The views of the scientists of the main process acting on the flat differ considerably. The first group of authors considers solifluction together with frost weathering the main process (*cf.* e.g. C. Wahrhaftig, 1965, p. 16; H. M. Eakin, 1916, p. 78; S. V. Obruchev, 1937, p. 59; Zh. M. Belorusova, 1963, p. 90, etc.). The second group claims that the main agent is the running water (*cf.* Kropachev & Kropacheva, 1956, p. 135; E. A. Vtyurina, 1966, p. 55). Finally, the third group of authors is of the opinion that on the flats a complex of processes with solifluction, sheet wash and levelling by shallow rills at the head play an important part (S. G. Boch & I. I. Krasnov, 1951, p. 52).

Observations in various areas and under various conditions have shown that on the prevailing part of the flats the frost sorting of deposits occurs. A whole number of forms can be found there — from spots of fine soil up to perfect polygons. On the margins of the flats the polygons pass over in stone stripes. But the cryoturbation processes only prepare and sort the material and cannot be the main transporting and accordingly modelling agent.

In contradistinction to it, solifluction phenomena occur only on flats where there is a sufficient quantity of fine soil. Solifluction tongues developed on the whole surface of the flats on the terraces levelling the shales on the Kular Ridge in Yakutia. Due to the weathering of shales a sufficient quantity of fine soil developed and the material was transported on the surface predominantly by

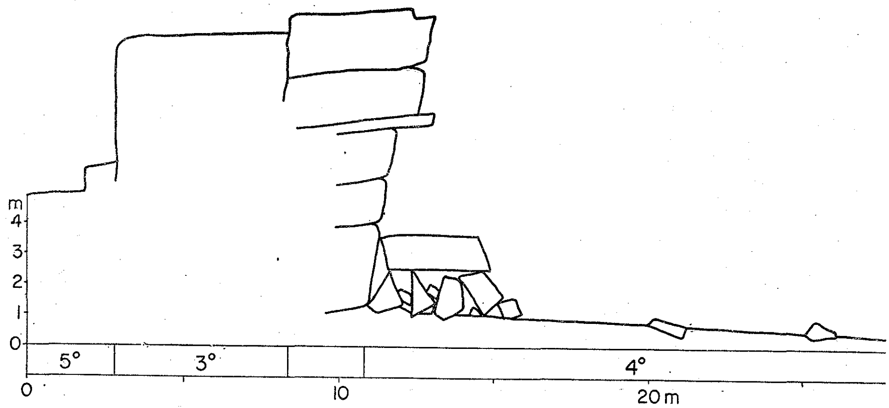

Fig. 2. Schematic sketch of the frost-riven cliff on the Táborské skály ridge, with the adjacent cryoplanation terrace

Levelled by J. Vařeka, constructed by J. Demek, 1964

solifluction. On the contrary, in the granitoids of the Aldanskoye Nagorye only a small quantity of fine soil develops by weathering. The flats are covered with angular block fragments. The finer material is evidently removed from the inter-spaces of the boulders by suffosion (subsurface running water erosion) and accumulates on the terrace margin. Active solifluction tongues are developed but on the terrace margin. Rill erosion could then be observed only on the terraces in the frost desert on the Kular Ridge in Yakutia where the vegetation was so sporadic that it could not avert the linear erosion and the soil was of silt with only small shale fragments. In those conditions the influence of deflation can be admitted even though it cannot be the main agent of transportation.

It may be then stated for just reasons that on the flats a complex of agents are acting, some of them being able to prevail according to local conditions (especially to bedrock properties and the consequent kind of products of weathering). Even under equal geological conditions with gradual refinement of the material and increase of the fine soil proportion the replacement of the prevailing process can take place as for instance the replacement of suffosion by solifluction.

With the gradual development of the cryoplanation terrace also the direction of the removal changes (*cf.* G. F. Gravis, 1964). The original direction of the removal is from the foot of the frost-riven cliff or frost-riven scarp and takes the nearest way to the outer terrace edge. But the direction changes gradually with the increase of the width of the terrace and the sideward removal begins to take place.

PROCESSES ACTING IN THE THIRD STAGE OF THE DEVELOPMENT OF A CRYOPLANATION TERRACE

In the third stage i.e. that of the cryoplanation summit flat, the inclination of the surface decreases as much as below 2°. In dependence on the bedrock composition the surface is covered with products of weathering of various grain size generally with larger or smaller bedrock fragments. On the surface of the flat cryoturbation processes are acting creating polygonal patterns of various dimensions. Owing to further development the products of weathering are usually finer-grained than those on the flats in the second stage of development. Due to the small inclination the activity of solifluction as well as that of running water almost cease. Suffosion is supposed to act, mainly the washing away of fine products of weathering into the fissures in the bedrock. Proof of it can be the nivation funnels found on these flats especially in the Evota Massif in the Aldanskoye Nagorye (*cf.* also L. Tyulina, 1931). Owing to a higher fine soil content and to the exposition of the flats on summits even the deflation can play an important part under favourable circumstances.

CONCLUSIONS

In the development of cryoplanation terraces a complex of cryogene processes is acting some of which prepare the material (nivation processes, frost weathering, frost sorting) and some transport the material down the flat surface (supranival processes, solifluction, surface and subsurface removal by running water, deflation). The share of the individual processes changes in dependence on the stages of the terrace development. In the first stage mainly processes connected with nivation are acting. In the second stage nivation acts on the frost-riven cliffs or frost scarps and on the terrace flat transportation processes manifest themselves. In dependence on the properties of the products of weathering of the bedrock on the flat either solifluction or surface and subsurface activity of running water can prevail. In the third stage —

that of the summit flat — mainly cryoturbation processes and in dependence on local conditions even deflation are acting.

References

Belorusova, Zh. M., 1963 — O nagornykh (soliflukcionnykh) terrasakh ostrova Bolshogo Lyakhovskogo (On the altiplanation — solifluction — terraces in the Bolshoj Lyakhovskij Island). In: Rutilevskij, G. L.-Sisko, R. K. (red.) — Novosibirskiye ostrova (The Novosibirskiye Islands), *Trudy Antarkticheskogo nauchnoissledovatelskogo Instituta Glavnogo upravleniya severnogo morskogo puti Ministerstva morskogo flota*, Leningrad; p. 88—92.

Boch, S. G., Krasnov, I. I., 1943 — O nagornykh terrasakh i drevnikh poverkhnostyakh vyravnivaniya na Urale i svyazannykh s nimi problemakh (Altiplanation terraces and old planation surfaces in the Ural Mts. and associated problems). *Izv. Vses. Geogr. Obshch*, t. 75; p. 14—25.

Boch, S. G., Krasnov, I. I., 1946 — K voprosu o granice maksimalnogo chetvertichnogo oledeneniya v predelakh Uralskogo khrebta v svazi s nabludeniyami nad nagornymi terrasami (On the problem of the limit of the maximum Quaternary glaciation within the Ural range as revealed by the study of altiplanation terraces). *Byull. chetvert. kom. Akad. Nauk SSSR*, 8; p. 46—72.

Boch, S. G., Krasnov, I. I., 1951 — Proces golcovogo vyravnivaniya i obrazovanie nagornykh terras (The process of goletz-planation and the formation of altiplanation terraces). *Priroda*; p. 25—35.

Eakin, H. M., 1916 — The Yukon—Koyukuk Region, Alaska. *U. S. Geol. Survey, Bull.* 631; 88 p.

Gravis, G. F., 1964 — Stadijnost v razvitii nagornykh terras — na primiere khr. Udokan (Stages in the development of altiplanation terraces — as exemplified by the Udokan range). *Voprosy Geogr. Zabajkalskogo Severa*, Moskva; p. 133—142.

Holmes, A., 1965 — Principles of physical geology. New York; 1288 p.

Jahn, A., 1961 — Quantitative analysis of some periglacial processes in Spitsbergen. *Nauka o Ziemi, II, Univ. Wrocławski, Zeszyty Naukowe*, ser. B, Nr. 5; 54 p.

Kropachev, A. M., Kropacheva, T. S., 1956 — Nagornyje terrasy odnogo iz rajonov vostochnogo Zapolyarya (Altiplanation terraces in one of the regions of the eastern Transpolar area). *Nauchn. Trudy, Minist. vysshego obrazovaniya SSSR*, Molotovskij Gornyj Inst., 1; p. 126—135.

Leef, L. D., Judson, S., 1965 — Physical geology. New Jersey; 406 p.

Lewis, W. V., 1939 — Snow-patch erosion in Iceland. *Geog. Jour.*, vol. 94; p. 153—161.

McCabe, L. H., 1939 — Nivation and erosion in West Spitzbergen. *Geog. Jour.*, vol. 94; p. 447—465.

Obruchev, S. V., 1937 — Soliflukcjonnye (nagornye) terrasy a ikh genezis na osnovanii rabot v Chukotskom krae (Solifluction — altiplanation — terraces and their origin, on the background of the studies in the Chukotka Land). *Problemy Arktiki*, 3; p. 27—48, 4; p. 57—83.

Popov, A. I., 1960 — Periglacyalnye obrazovaniya severnoj Eurazii i ikh geneticheskie tipy (Periglacial phenomena of northern Eurasia and their genetic types). In: *Periglacyalnye yavleniya na territorii SSSR*, Moskva.

Read, H. H., Watson, J., 1964 — Introduction to geology. London; 693 p.

Tyulina, L., 1931 — O yavleniyakh svyazannykh s pochvennoj merzlotoj i moroznym vyvetrivaniem na gore Iremel — Yuzhnyj Ural (On the phenomena associated with permafrost and frost weathering on the Iremel Mt., Southern Ural). *Izv. Gos. Geog. Obshch.*, t. 63; p. 124—144.

Vtyurina, E. A., 1966 — Kriogennye sklonovye terrasy (Cryogenic slope terraces). Moskva; 95 p.

Wahrhaftig, C., 1965 — Physiographic divisions of Alaska. *U. S. Geol. Survey, Professional Paper* 482; p. 1—52.

DISCUSSION

Professor Jahn: Cryoplanation terraces in Siberia and in the Hrubý Jeseník Mts. in Czechoslovakia are very similar — both are covered by vegetation, lichens. Which terraces are fossil and which ones are active, and what arguments support the opinion on the activity of cryoplanation processes in Siberia?

Dr. Demek: The cryoplanation terraces in the Hrubý Jeseník Mts. are fossil forms of Pleistocene age. They are mostly covered with vegetation. The measurements of block-movement we have been carrying out here since 1963 did not show any movements of debris even on slopes grading 33°. Similar fossil terraces are in Siberia in the taiga zone. I had the opportunity to study those fossil terraces near the village of Khuzino in the mountain range Vostochnyj Sayan at the altitude of about 1000 m.

Cryoplanation terraces, presented on the slides, in the region of the Aldanskoye Nagorye, and that of the Evota Massif in particular, are in my opinion the terraces which also develop under the present-day conditions. This fact is proved by such phenomena as fresh boulders at the foot of the frost-riven scarp, active polygonal grounds and especially solifluction terraces on the outer margin of the cryoplanation terraces. Traces of the activity of snow-patches can be found at the foot of the frost-riven scarp.

Similarly, the terraces on the Kular Ridge are active in the present time, but their development might have been more intensive in the Pleistocene.

Professor Rudberg: Have you any data on the rate of cryogene processes? In the Swedish high mountains (frost shatter zone) there are very flat surfaces with tor-like features. These forms are very similar to the terraces in Siberia, demonstrated on slides. In my opinion — but it is not proved — the surfaces in the Swedish mountains originated from some sort of roche moutonné, probably during the last glaciation. These forms have disappeared except for some remnants.

As to the contemporaneous processes it is clear that the frost weathering attacks the rock scarps (snow patches and water-saturated material at the scarp bases). My scattered measurements reveal that the present-day movement seems to be quite slow, but it might have been greater before the formation of the contemporaneous stone pavements.

Dr. Demek: As far as I know there are till now no data on the rate of the development of cryoplanation terraces. The rate can be judged only indirectly mainly if — as you have correctly mentioned — remodelled glacial forms are considered. S. G. Boch and I. I. Krasnov (1946) quote from the Ural that the cryoplanation terraces in the Salner and Neroyki Massifs are developed on steps in very young glacial cirques. During the excursion of the INQUA Congress in the USA in 1965, we saw — with Professor A. Jahn — cryoplanation terraces in the saddle of the Glacier National Park (Montana) that was in the Würm (Pinedale Stage) entirely covered with a glacier. In Novaya Zemlya the terraces occur — according to Boch and Krasnov — in places recently deprived of the glacial mantle. Finally, Professor Waters described from Spitsbergen small terraces in an area exposed by the regression of the glacier 10,000 years ago.

It can be accordingly supposed that the terraces may develop relatively quickly under favourable conditions. But the rate of development can be very different and especially larger terraces develop obviously rather long.

Professor Washburn: What can Dr. Demek tell us about the role of structure in the development of cryoplanation terraces?

Dr. Demek: Cryoplanation terraces occur in all kinds of rocks. In some rocks (e.g. in gneiss, quartzite, sandstone, basalt) they are found more often than in other rocks. In many places it has been established that cryoplanation terraces level rocks of various resistance to cryogene processes. On the other hand the structure exerts indisputably a certain influence upon the development of the terraces. H. M. Eakin has already mentioned in his work from Alaska (1916) that the terraces are found on one mount whereas they are not developed on another mount of the same appearance and geologic structure. In the development of terraces a considerable part is played by the jointing especially by vertical fissures which promote the parallel backwearing of frost--riven cliffs. We find also terraces occurring on the contact of two rocks of various resistance (e.g. sandstone and shale); the terrace being usually developed in the less resistant rock while the frost-riven cliff — in the more resistant rock. Even such terraces were found whose surface is conformable to the rock layers and which can be designated as structural forms. However most terraces are forms developing without a more important dependence on geologic structure.

Dr. Dumanowski: Geological structure, and especially the texture of rocks, exerted a great influence upon the development of slope terraces which can develop not only in periglacial areas. Such terraces are also known in the areas which were under climatic conditions different to the periglacial ones.

Dr. Demek: I have already stressed in my paper that the uneven slope surface is the necessary condition of the origin of cryoplanation terraces. Some terraces may even be remodelled terrace-like forms of the period before the coming of the periglacial climate. On the other hand it is obvious that in periglacial climate a characteristic type of terrace-like forms develops. These terraces designated by the suggested name of cryoplanation terraces should be, in my opinion, distinguished from similar forms developed due to other complex of processes in other clima-morphogenetic zones.

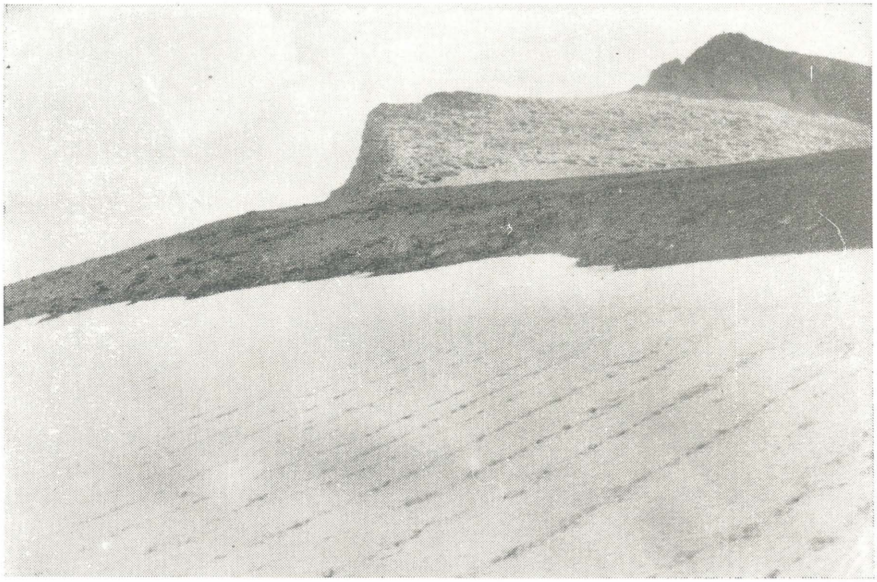

Photo by J. Demek, August 1965

Pl. 1. Snow patches in the Piegan Pass, in the Glacier National Park (Montana). Traces of boulders rolling down the snow field are visible on the snow surface

Photo by J. Demek, August 1966

Pl. 2. Traces of nivation processes at the foot of the frost-riven scarp on the Turku Mount in the Kular Ridge (Yakutia)

Photo by J. Demek, August 1956

Pl. 3. Polygonal grounds on the cryoplanation terrace in the Evota Massif in the Aldanskoye Nagorye (Yakutia)

Photo by J. Demek, August 1956

Pl. 4. Solifluction terracettes and tongues on the margin of the cryoplanation terrace in the Evota Massif (Yakutia)

Photo by J. Demek, August 1936

Pl. 5. Nivation hollows on the cryoplanation summit flat in the Evota Massif (Yakutia)

Photo by J. Demek, August 1966

Pl. 6. Polygonal grounds on the cryoplanation summit flat in the Evota Massif (Yakutia)